THE APPLICATION OF THE NEW ‘NEW EXTENSION FLOOR SLAB’ METHOD OF CONSTRUCTION TO EXISTING BRIDGE AND ITS DESIGN

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ABSTRACT

In Japan, extension floor slab construction has been utilized as one of effective reduction countermeasures of vibration and noise induced at a bridge site. In this construction system, the bridge floor slab is extended to reach the topsoil at the back of an abutment. Then, because an expansion joint is installed at a distance from the bridge, the vibration induced at the expansion joint can be reduced without transmitting to the bridge.

Over the past several years, Public Works Research Institute (PWRI) has conducted joint research with Japan Bridge Association (JBA) on new extension floor slab systems. As the joint studies, a new extension floor slab system was adapted to an actual bridge. This paper describes the outlines of the new extension floor slab system and the vibration characteristics of the bridge with and without the extension floor slab. To study the design procedure for determining the length of the extension floor slab and the vibration characteristics of the bridge, the field vibration measurements and the numerical simulation of bridge vibrations were carried out. The effects on vibration reduction were evaluated from the experimental and numerical results.

1. INTRODUCTION

There has come stronger demand for comfortable roadside environments adjacent living space, particularly as regards to reducing vibration and noise from infrastructures.[1] Therefore, the construction cost of environmental countermeasures such as noise insulation walls has risen compared to other road construction costs.

Primary sources of vibration and noise are bridges and other road facilities; especially bridge expansion joints have drawn the greatest attention. Although concrete jacketing is commonly used on girder ends to reduce vibration and noise at expansion joints [2], its effectiveness is not sufficient.

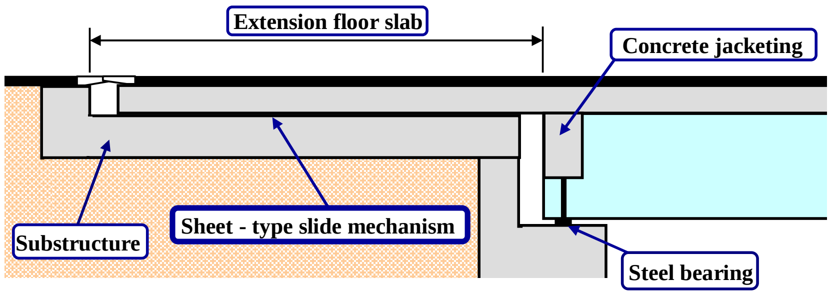
Recently, as one of more effective countermeasures, the former Japan Highway Public Corporation (JH) has utilized extension floor slab construction method. In this construction method, the bridge floor slab is extended to reach the topsoil at the back of an abutment. Then, an expansion joint is installed at a distance from the bridge, so the vibration induced at the expansion joint can be reduced without transmitting to the bridge. To date, similar countermeasures have been applied in more than ten actual bridges.[3],[4]

Over the past several years, Public Works Research Institute (PWRI) has conducted joint research with Japan Bridge Association (JBA) on the structural design of an extension floor slab. As part of the joint researches, the newly developed extension floor slab system was installed to an existing bridge. This paper describes the outlines of the newly developed extension floor slab system and the vibration characteristics of the bridge before and after the installation of the extension floor slab. To study design procedure for determining the length of an extension floor slab and the vibration characteristics of the bridge, the field measurement and numerical simulation of bridge vibration were carried out.

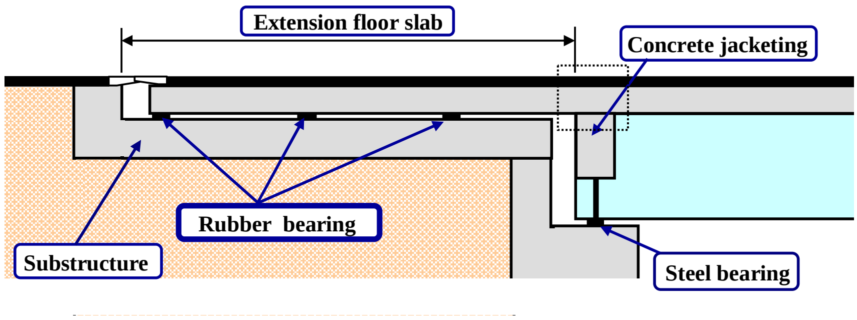
2. FUNDAMENTAL STURUCTURE OF EXTENSION FLOOR SLAB

Figure 1 (a) shows the fundamental structure of an extension floor slab installed to date. Since

the extension floor slab moves simultaneously with a bridge, a sliding mechanism must be provided between the extension floor slab and the bridge substructure. The unique structural feature of the extension floor slab, shown in Figure 1 (a), is to have a plane sheet for the slide mechanism. The authors call this, a “sheet-type” structure. The sheet-type slide mechanisms have been constructed of asphalt-type sheets, stainless plate with sand, stainless steel and polyethylene resin, and concrete on concrete. In the sheet-type structure, the extension floor slab is supported on a plane sheet, so the vibration generated at an expansion joint is directly transmitted to ground. However, due to the high friction of the sheet plane, girder movements may be restricted during live loadings and temperature changes. So, the authors developed the new extension floor slab with a smoother slide mechanism. Figure 1 (b) shows the outline of the new extension floor slab. As the sliding mechanism of the extension floor slab, the rubber bearings with a slide surface were used.



(a) Sheet – type bearing



(b) Rubber bearing

Figure 1. Two types of extension floor slab with different slide mechanism

3. OUTLINE OF CONSIDERED BRIDGE AND INSTALLED EXTENSION FLOOR SLAB

The considered Bridge, shown in Figure 2, consists of double three-span continuous steel plate girder bridges, with a total length of 188.2 m and a width of 9 m. The new extension floor slab was installed on the three-span continuous steel plate girder on the A2 side. Figure 3 shows the outlines of the installed extension floor slab. The extension floor slab, the stringer and the cross beam were built of pre-cast concrete. As describe later, the length of the extension floor slab given by experimental design formula is about 6m. However, to avoid interference with the existing underground structure, the extension floor slab with a length of 10m was installed.

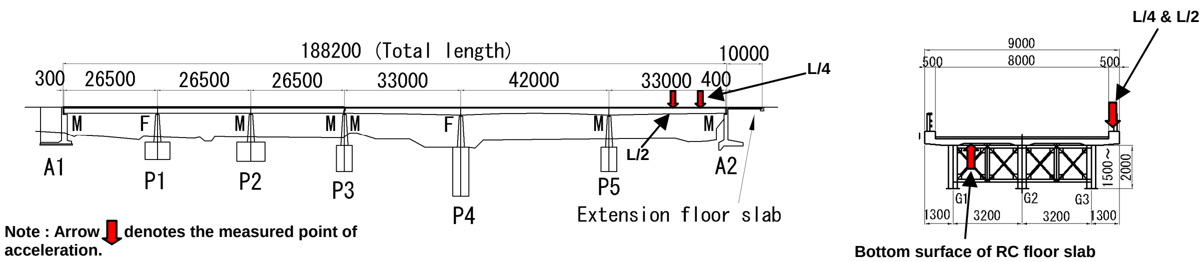


Figure 2. Outline of considered bridge

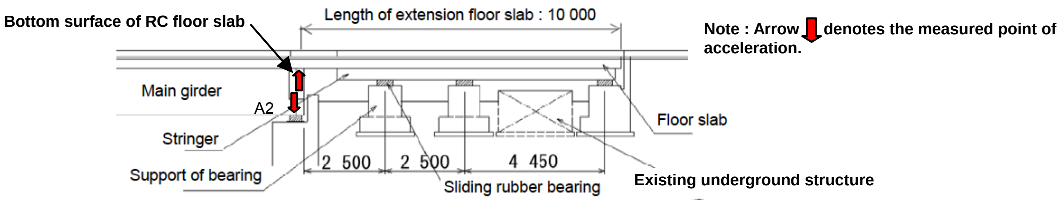


Figure 3. Outline of extension floor slab

By the way, as our research programs, the following engineering issues were treated.[5] This paper describes the experimental design formula for estimating the length of an extension floor slab in the 2nd issue and the 3rd issue.

- Static behavior of an extension floor slab due to live loadings and temperature changes: Especially, the stress concentration of the base of the installed extension floor slab, for which portion is shown by dot line in Figure 1 (b), was studied and the effects of the countermeasures for the stress reduction were verified by 3D FEM analysis and actual static loading tests in the field.
- Rational design procedure of an extension floor slab: The empirical design formula for estimating the length of an extension floor slab was derived through the driving test using actual vehicles. Also, to study the structural design procedure of an extension floor slab, 3D frame analysis of the bridge with an extension floor slab was carried out.
- Dynamic behavior due to a moving vehicle and reduction of vibration and noise: The field vibration tests using test vehicles and the dynamic response analysis using 2D frame model were carried out.
- Construction procedure of extension floor slab for improvement project of existing bridges
- Inspection method for maintenance of rubber bearing

4. EXPERIMENTAL DESIGN FORMULA OF LENGTH OF EXTENSION FLOOR SLAB [6]

The length of an extension floor slab must be determined in a design stage. Two performance requirements will be considered in the determination of the length: (1) vehicle vibrations generated at an expansion joint must be markedly reduced without transmitting to a bridge girder; and (2) the end of an extension floor slab must not lift up when a live load is applied to a bridge (see in Figure 4). To study the length of an extension floor slab for vibration reduction, we carried out the driving tests of actual vehicles on PWRI test roads and other locations. The test vehicles had about 245kN weight and three axles with leaf or air suspension system. The dynamic responses of the vehicles were measured in the different conditions of vehicle speed (about 40 and 80 km/h), pavement types (asphalt and elastic pavement) and road bump height (0, 10, and 20 mm). Figure 5 shows the measured points for estimating vehicle vibrations. In general, two vibrations of the suspension and tire spring systems of a vehicle are studied. In this paper, we call the former "1st vehicle vibration" and the latter "2nd vehicle vibration", respectively.

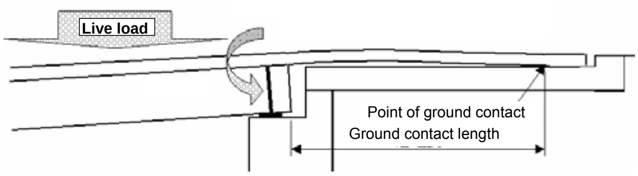


Figure 4. Static behavior of extension floor slab due to live loading

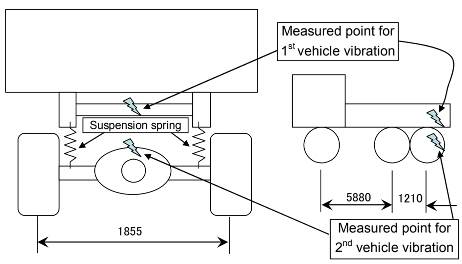
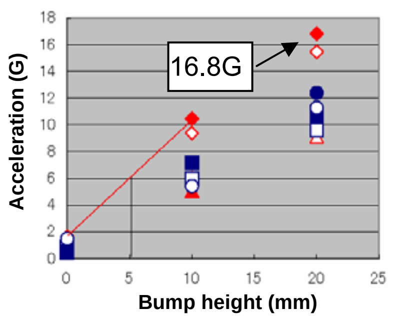


Figure 5. Measured points of vehicle vibration

Figure 6 shows the measured acceleration corresponding to the 2nd vehicle vibration. The maximum acceleration under the most conservative conditions with a vehicle speed of 80 km/h and a bump height of 20mm was 16.8G. G (= 9.8m/s^2) denotes gravity acceleration. With a bump height of 10mm, it was 10.5G. The threshold of the bump height for the repair of expansion joints is 10 – 20mm.[7] The normal bump height is considered to be half the repair threshold or 5 mm. Figure 8 shows that the maximum acceleration under the most conservative condition becomes about 5G at a bump height of 5 mm. So, as the target of vibration reduction, it was decided the maximum acceleration of 16.8G was reduced to 5G.



Notation

Plot	Suspension	Vehicle speed (km/h)	Pavement
■	Leaf	40	Asphalt
●		80	
□		40	Elastic
○		80	
▲	Air	40	Asphalt
◆		80	
△		40	Elastic
◇		80	

Figure 6. Measured acceleration vs. bump height

Assuming that the acceleration A_L (2nd vehicle vibration) induced at an expansion joint decay to a fixed vibration acceleration level A_0 as a vehicle moves to a bridge over an extension floor slab, the logarithmic decrement of the damped free vibration can be expressed as follows:

$$\delta = \left(1/n\right)\ln\left(A_L / A_0\right) \tag{1}$$

Where:
δ : logarithmic decrement
n : wave number of the vehicle vibration during the passage of a vehicle on an extension floor slab
A_L : acceleration [G] of the vehicle vibration induced at an expansion joint
A_0 : acceleration [G] of the vehicle vibration when a vehicle reaches to a bridge

The relationship between the wave number n and the length L of an extension floor slab is expressed as follows:

$$n = 3.6\frac{Lf}{V_m} \tag{2}$$

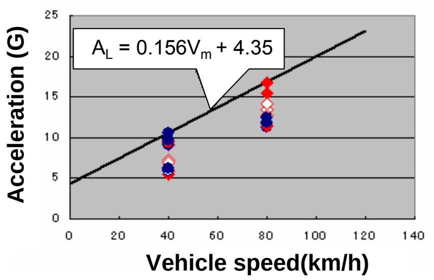
Where:
L : length of an extension floor slab [m]
f : natural frequency of tire - spring system (2nd vehicle vibration) [Hz]
V_m : vehicle speed [km/h]

Thus, the relationship between A_L and A_0 can be expressed as follows:

$$A_L = A_0 \exp\left(3.6\frac{Lf\delta}{V_m}\right) \tag{3}$$

Figure 7 shows the relationship between the vehicle speed and the acceleration of the 2nd vehicle vibration under the condition of a bump height of 20 mm. The regression equation on A_L, was given using the maximum values of the measured acceleration so that the estimated length of an extension floor slab becomes a conservative side. Moreover, from this driving tests, the dynamic properties of f = 11.3 Hz and δ = 0.26 for the 2nd vehicle vibration were obtained. Substituting the regression equation into equation (3), the experimental design formula for estimating the length of an extension floor slab was derived as follows.

$$L = \ln\left(A_L / A_0\right)\cdot V_m / 3.6 f\delta \fallingdotseq \ln\left(\frac{0.156V_m + 4.35}{5}\right)\cdot\frac{V_m}{10.58} \tag{4}$$



Notation

Plot	Suspension	Pavement
●	Leaf	Asphalt
○		Elastic
◆	Air	Asphalt
◇		Elastic

Figure 7. Measured acceleration vs. vehicle speed

Finally, the estimated length of an extension floor slab for each design vehicle speed was given in Table 1.

Table 1. Estimated length of extension floor slab vs design vehicle speed

Design vehicle speed (km/h)	Length of EFS (m)
40	3
60	6
80	10

Note : EFS denotes extension floor slab. The length of an extension floor slab must be no less than the landing length shown in Figure 4.

5. EXPERIMENTAL AND NUMERICAL STUDIES OF VIBRATION REDUCTION BY EXTENSION FLOOR SLAB

This chapter describes the field measurements and numerical simulation of bridge vibrations for evaluating the vibration reduction by the installed extension floor slab. Comparison is also made on the bridge vibrations due to a moving vehicle before and after the installation.

5.1 Field Vibration Test

Field vibration tests using test vehicles were carried out to measure the dynamic responses of the bridge before and after the installation of the extension floor slab. The test vehicle has single axis for the front wheels and double axles for the real wheels with leaf suspension systems. Table 2 summarizes the natural frequency and structural damping of the test vehicles. The certified weight of the test vehicle was about 245 kN.

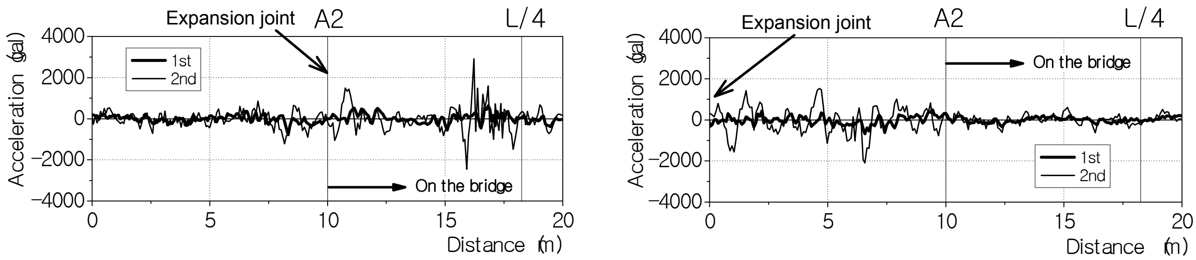
The test vehicles used were of different manufacturers, but the inherent dynamic properties of the 1st and 2nd vibrations of the vehicles used before and after the installation of the extension floor slab had no difference. Thus, it was thought that a series of tests were carried out in similar test conditions. The main measured points in the considered bridge are shown by ⬇ in figure 2 and 3. Attention was paid to the acceleration responses at the bottom surface of the RC floor slab, L/2 point (wheel guard on the G1 side) and A2 bridge abutment to study the impact responses due to the test vehicle.

Table 2. Dynamic properties of test vehicles used in field vibration tests before and after installation of extension floor slab

		Before		After	
		1st	2nd	1st	2nd
Natural frequency (Hz)	Measured	3.1	12.0	3.3	11.9
	Calculated	3.2	12.1	3.2	12.1
Log. decrement	Measured	—	0.34	0.27	0.36
	Calculated	—	0.42	—	0.42

Figure 8 shows the acceleration responses of the 1st and 2nd vehicle vibrations before and after the installation of the extension floor slab. The X axis of this figure shows the distance (the location of the vehicle) from the expansion joint installed after the installation of the extension floor slab. Before the installation of the extension floor slab, when the front and rear wheels of the vehicle pass on the expansion joint installed at A2 abutment, the impact responses occurred at x = 10m and 16m, respectively.

On the other hand, after the extension floor slab was installed, the impact responses occurred at x = 0m and 6m, respectively. After the installation, the impact responses were damped on the extension floor slab and reduced without transmitting to the bridge. The maximum amplitude (about 2G) of the 1st and 2nd vibrations was almost equal before and after the installation, so the external forces due to the moving vehicles before and after the installation were also considered to be almost equal.



(a) Before installation of EFS

(b) After installation of EFS

Note : EFS denotes extension floor slab.

Figure 8 Acceleration responses of 1st and 2nd vehicle vibrations before and after installation of extension floor slab

Figures 9 - 11 summarizes the acceleration responses, before and after the installation of the extension floor slab, at the bottom surface of the RC floor slab, L/2 point and A2 abutment. Although the various measured points gave different responses, it can be seen that, in all locations, the peak values of the acceleration responses were reduced by the installation of the extension floor slab. Especially, the acceleration response at the bottom surface of the RC floor slab (Figure 9), where the impact force from the vehicle is most directly applied, shows a marked reduction. For reference, the acceleration responses at the L/2 point were converted into the vibration level as shown in Figure 12. The vibration levels calculated using exponential averaging method show a reduction of about 15dB, from 78dB before the installation to 63dB after the installation. From the above results, it was verified that the influences of the vehicle vibration induced at the expansion joint became small by the installation of the extension floor slab.

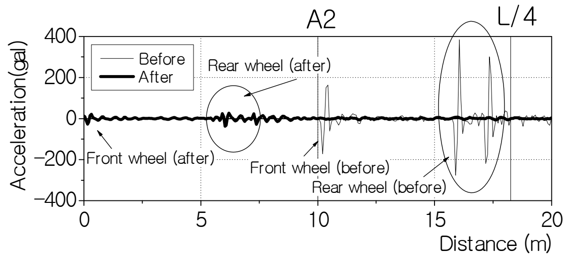


Figure 9. Acceleration responses at bottom surface of RC slab of bridge near A2 abutment

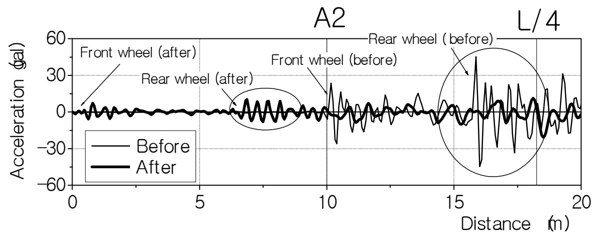


Figure 10. Acceleration responses at L/2 point

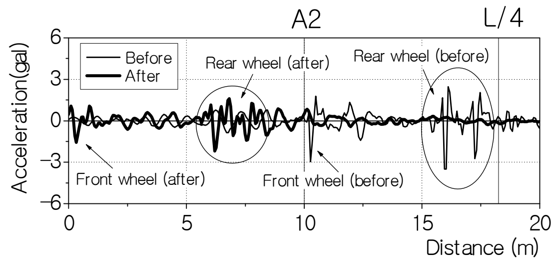


Figure 11. Acceleration responses at A2 abutment

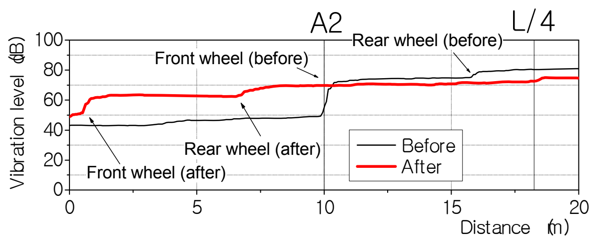


Figure 12. Vibration levels at L/2 point

5.2 Numerical Simulation of Bridge Vibration Due to Moving Vehicle [8]

(1) 2D Frame Model of Considered Bridge

The effects of an extension floor slab are studied through the numerical simulation of bridge vibrations. In this analysis, a two-dimensional frame model was used. Figure 13 shows the 2D frame model of the bridge with an extension floor slab. The bridge designed to be a three-span continuous non-composite girder. The flexural rigidity of the beam of the frame model was determined based on the natural frequency analysis obtained by 3D FEM analysis, for which stiffness of all members except for the pavement was considered.

In the frame model, roadbeds were also provided at both ends of the main bridge. The purpose of the roadbed on the A2 side was to make the vehicle generate a steady state vibration up to the point where a vehicle enters the bridge, and the roadbed on the P3 side is to simulate the damped free vibration of the bridge after a vehicle leaves the bridge. The roadbed was modeled as the beam on an elastic foundation with discrete spring elements, and the extension floor slab was modeled as the beam supported by spring elements of rubber bearings.

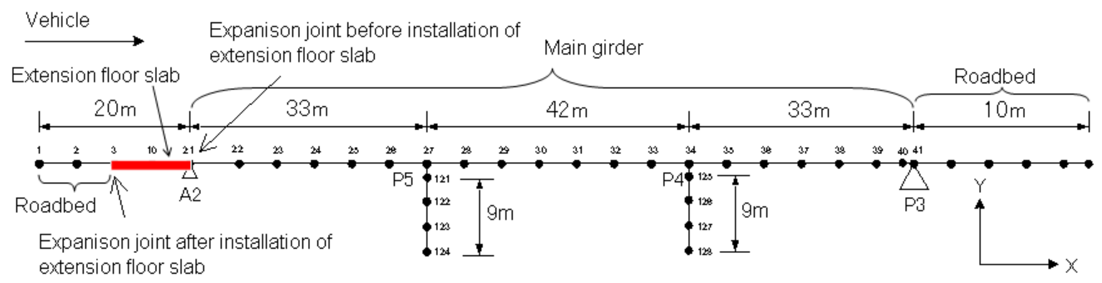


Figure 13. 2D frame model of considered Bridge

(2) Vibration Model of Moving Vehicle

Bridge vibration varies by the vibration properties of a moving vehicle. The numerical simulation of the bridge vibration was carried out using the vehicle model that had the same dynamic properties as the test vehicles used in the abovementioned driving test: 3 axles, five degrees of freedom system (tandem rear axle) (see Figure 14).

The dynamic properties of the vehicle model provided by the vehicle manufacturer were adjusted to so that the natural frequency and structural damping of the key vibration modes were compatible to the actual measurements. The weight of the mass on the spring was also adjusted to match the total weight of the test vehicles (245kN). Table 2 gives the dynamic properties (natural frequency and structural damping) of the vehicle model. Both the natural frequency and structural damping of the vibration model agree with the measured values quite well.

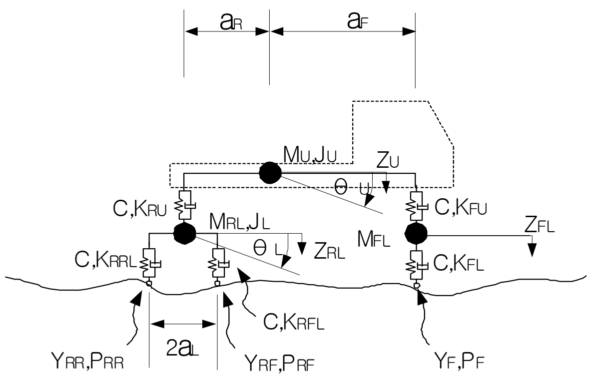


Figure 14. Vibration model of test vehicle

(3) Road Surface Roughness

It is best, in a dynamic response analysis, to use actual road surface roughness; however, the actual measurements of road surface roughness were not carried out. For the Monte Carlo simulation of road surface roughness, the known power spectral density of road surface roughness was used.[9] The design vehicle speed of 60 km/h was given. The surface roughness used in the analysis is shown in Figure 15. In this study, comparison was made on the actual measurements in the earlier service stage of the bridge, so the road surface condition was evaluated to be very good. Therefore, the surface roughness data, which agreed with the power spectral density function with the road surface condition corresponding to ISO class A, was used, as shown in Figure 16. A bump of 9mm was also given to simulate the road bump at the expansion joint. This bump is equal to the lower limit of repair requirement threshold (9 – 10mm).

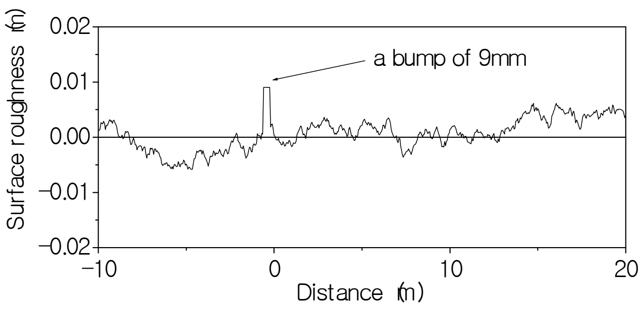


Figure 15. Road surface roughness

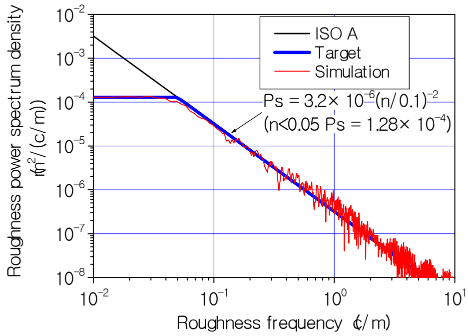
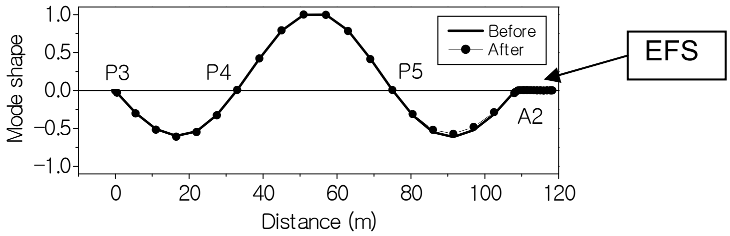


Figure 16. Power spectrum density of road surface roughness

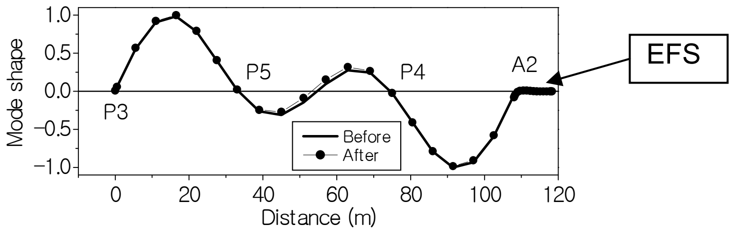
5.3 Numerical Results and Discussion

(1) Natural Frequency

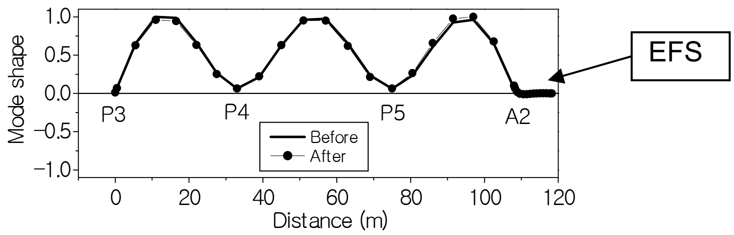
The 1st, 2nd and 3rd mode shapes of the bridge before and after the installation of the extension floor slab are shown in Figure 17. Table 3 gives the calculated and measured natural frequency before and after the installation. There results agree well with only a -5% to -9% margin of error. Therefore, it was verified that the analysis model was valid. The natural frequency of the bridge before and after the installation shows no marked difference. Although there was some difference at the A2 abutment, where the extension floor slab was located, the overall mode shapes after the installation are almost equal to those before the installation.



(a) Bending 1st mode



(b) Bending 2nd mode



(c) Bending 3rd mode

Note : EFS denotes extension floor slab

Figure 17. Calculated Mode shapes of bridge before and after installation of extension floor slab

Table 3. Calculated and measured natural frequency

Mode No.	Before			After		
	①Calculated	②Measured	①／②	①Calculated	②Measured	①／②
1	2.23	2.44	0.91	2.25	2.41	0.93
2	3.41	3.61	0.95	3.46	3.78	0.92
3	4.17	4.39	0.95	4.20	4.49	0.94

(Unit : Hz)

(2) Vehicle Response

Figure 18 shows the acceleration responses of the concentrated mass on the front and rear wheels of the vehicle at a vehicle speed of 60km/h. For the simulation of the surface roughness before and after the installation of the extension floor slab, the sample functions of the surface roughness with same phase angles, which were generated by using random number generator, were used. Then, the vehicle responses before and after passing over a bump were equal, so comparison before and after the installation of the extension floor slab was not made.

The figure also shows that the impact responses of the mass on the front and rear wheels, when they pass over the bump (at distances of 10 m and 16 m, respectively), generated and dampen in a few meters. The result shows that the impact responses due to the bump dampen on an extension floor slab of 10m and the vehicle response becomes the steady state responses under the condition of normal road surface roughness. Because the reference points are different, comparison can not be made with Figure 8. However, the simulated impact responses correspond to the fluctuation pattern of the measured responses well.

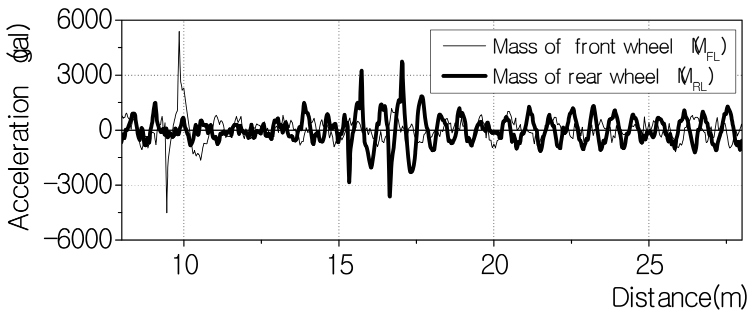


Figure 18. Numerical simulation of vehicle response (Simulation)

(3) Bridge Vibration

Comparison was made between the measured and numerical dynamic responses (at a vehicle speed of 60 km/h) before and after the installation of the extension floor slab. In this paper, as the reference point for comparison, the acceleration at the L/2 point was selected because the results can be compared directly. Figure 19 shows the acceleration responses and its vibration levels (dB) at the L/2 point. Before the installation of extension floor slab, the large impact response was generated as the vehicle entered the bridge. It can be seen that the numerical and measured dynamic responses have a similar tendency. The vibration levels of the simulated dynamic responses agreed with the measured values after passing A2 abutment well.

On the other hand, it was recognized that the impact responses were markedly reduced after the installation of the extension floor slab. The vibration levels, generated by the rear wheels before and after the installation of extension floor slab, were reduced by 10 dB, from 80dB before the installation to 70 dB after the installation. The numerical results also show the similar effects, and both the responses and vibration levels agreed with the measured values well. The post-installation measurements were conducted 1.5 years after the pre-installation measurements, so the road surface conditions may have deteriorated. As reference, another calculation was done using surface roughness of ISO class B (shown in Figure 19); this numerical simulation agreed even better with the above measured results.

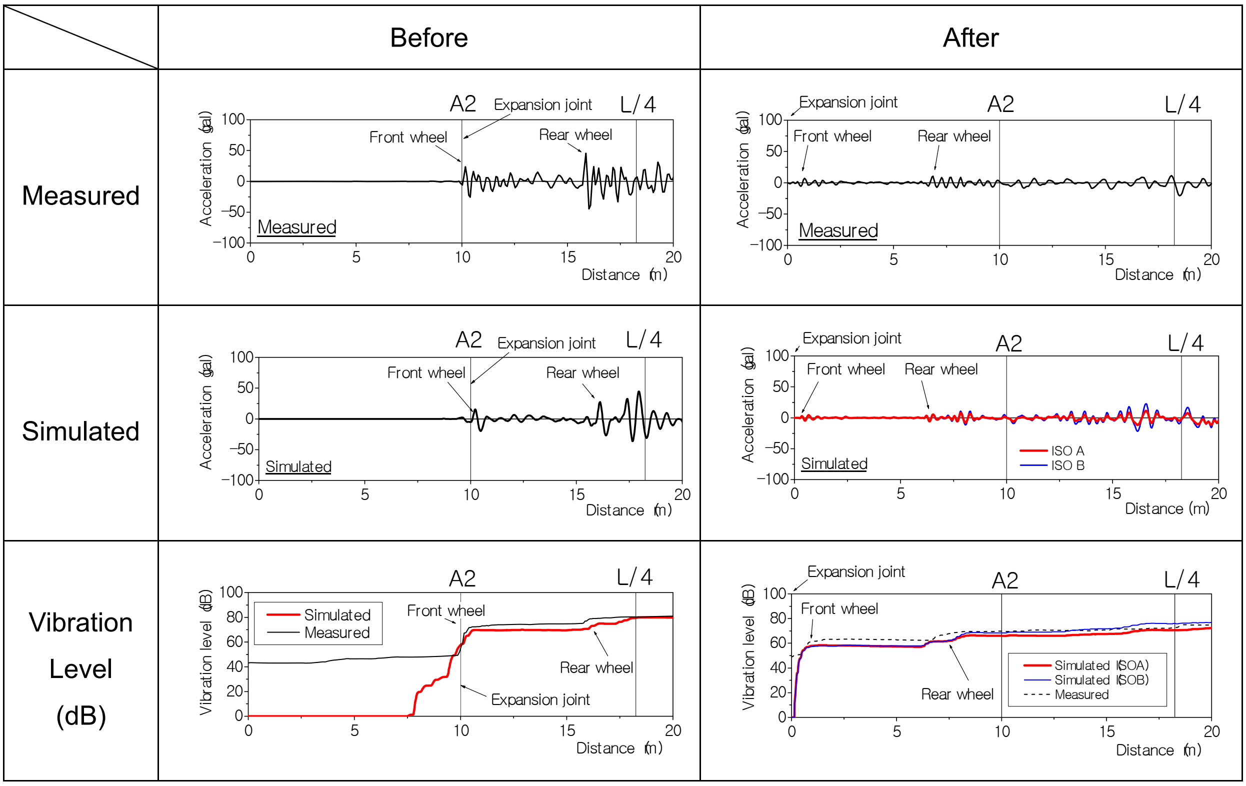


Figure 19. Acceleration response at L/2 point before and after installation of extension floor slab (Comparison between measured and simulated results)

(4) Comparison on Length of Extension Floor Slab

1) Natural Frequency

Different length of extension floor slab, 10m, 8.2m, 6.4m, and 3.9m, were used to study their respective effectiveness. Natural frequency of the analysis model is shown in Table 4. There were no marked differences in natural frequency before and after the installation of extension floor slab, and among the different slab length.

Table 4. Change of natural frequency according to length of extension floor slab (Calculated)

Mode No.	Before	After, Length of EFS (m)			
		10	8.2	6.4	3.9
1	2.23	2.25	2.25	2.25	2.26
2	3.41	3.46	3.46	3.46	3.48
3	4.17	4.20	4.20	4.20	4.22

(Unit : Hz)

Note : EFS denotes extension floor slab.

2) Bridge Vibration

The difference on the length of extension floor slab was studied with a focus on the vertical acceleration at the L/2 point located between A2 and P5. Figure 20 shows the acceleration responses before and after the installation of extension floor slab (with length of 10m and 3.9 m). The impact responses induced at the expansion joint is markedly reduced after the installation. Comparison for the different slab length also shows that the shorter the slab length is, the larger the impact responses become.

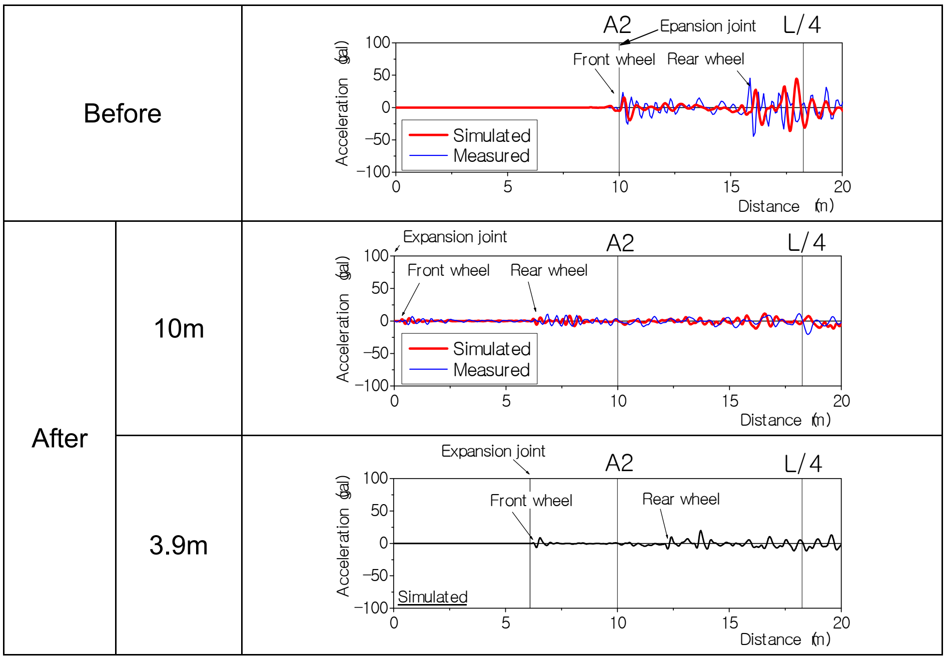
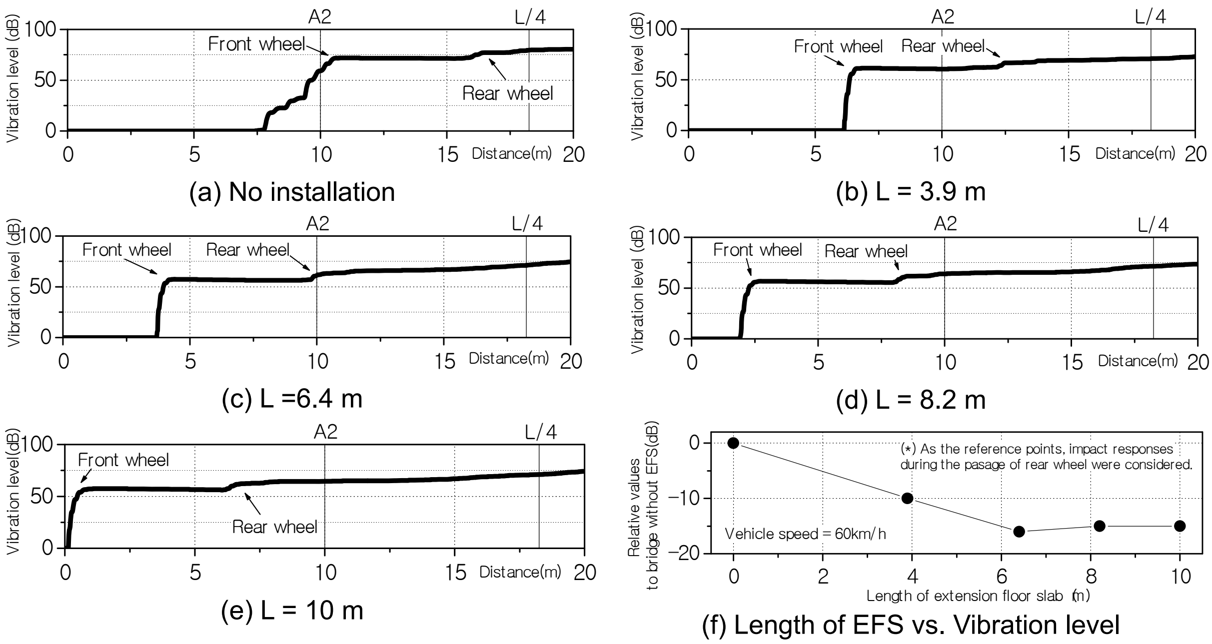


Figure 20. Acceleration response at L/2 point before and after installation of extension floor slab (Length of extension floor slab : 10 & 3.9 m, Vehicle speed : 60km/h)

3) Vibration Level

The effect of the length of the extension floor slab was evaluated based on vibration levels (dB). Figure 21 shows the vibration levels at the L/2 point for the different slab length. The figures show that the impact responses were generated when the front and rear wheels passed over the expansion joint. Focusing on the impact response peak for the real wheels, Figure 21(f) shows the relationship between the length of extension floor slab and the relative value of the peak vibration levels (at vehicle speed of 60km/h; relative to conditions without extension floor slab). The effect of the vibration reduction converges at a length of 6 m or more, reducing the vibration down to about 15 dB. This result also agreed with the length obtained through the experimental design formula of the length of an extension floor slab discussed in Chapter 4.



Note : EFS denotes extension floor slab

Figure 21. Comparison on length of extension floor slab (Simulation, Vehicle speed : 60km/h)

6. CONCLUSIONS

This paper describes the outlines of new extension floor slab systems and the vibration characteristics of the bridge with and without an extension floor slab. Conclusion remarks summarize as follows.

1) Two types of the extension floor slab with different slide mechanisms between the extension floor slab and the bridge substructure were introduced. In order to provide the slide mechanism with low friction, the extension floor slab with a slide rubber bearing was newly developed. And, the extension floor slab was installed to an existing bridge.
2) Focusing on the reduction of vehicle vibrations during moving on an extension floor slab, the experimental design formula for estimating the length of an extension floor slab was obtained through the driving tests of actual vehicles in the field.
3) In order to study the effect of an extension floor slab on vibration reduction, the field vibration tests using actual vehicles before and after the installation of the extension floor slab were carried out. It was verified that the vehicle vibrations induced at an expansion joint were reduced by the installation of the extension floor slab.
4) Numerical simulation of bridge vibrations due to moving vehicles was carried out. The numerical and measured dynamic responses had a similar tendency. Moreover, comparison was made on the length of extension floor slab. The effect of the vibration reduction converged at a length of 6 m or more. This result also agreed with the length obtained through the experimental design formula of the length of an extension floor slab

Finally, the authors are currently developing a three-dimensional traffic vibration simulation program considering shell elements. In the simulation program, the effects of the local vibration of a floor slab and bridge members will be considered to study on vibration reduction mechanism in detail.

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